# EXTENSIVE SIMULATION OF HUMAN-ROBOT INTERACTION FOR CRITICAL CARE TELEMEDICINE

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## ABSTRACT

This article proposes a new immersive digital-twin simulation framework, dubbed Extensive Simulation, aimed at high-precision analyses of human-robot interaction (HRI) for critical care telemedicine, or tele-ICU. The proposed approach first reproduces in a virtual ICU environment, the real-time digital replica of physical robot navigating under ICU care setting. Then, the digital twin constructed in the virtual environment is extended with immersive simulation technology, to elicit and collect interactive human behaviors from diverse group of tele-ICU users (including physicians, nurses, and technical staffs either onsite or remotely located, along with patients and guardians). The proposed Extensive Simulation framework advances digital twin concept by including humans into the loop via immersive simulation, which will help reliably capture diverse human behaviors and construct human model for tele-ICU work system.

**Keywords:** Digital Twin, Immersive Simulation, Human-Robot Interaction, Tele-ICU.

## 1 INTRODUCTION

Robotic systems are used in various healthcare contexts (Kyrarini et al. 2021), including robotic *telepresence* (interchangeably, telehealth, remote presence, or telemedicine). Intensive care unit (ICU) is one of the last places that have not integrated robots into clinical workflows due to potential issues and concerns (Reck 2022) of their acceptance. One of the fundamental unknowns in accepting robotic telepresence for ICU is the knowledge of flexible human-robot interaction (HRI), which might be determined by specific patient-care goal and care environment. This article envisions high-fidelity simulation and analyses of HRI based on that simulation will potentially address such knowledge gap. The goal of this article is to propose a new simulation framework (dubbed Extensive Simulation), enabling quantitative simulation-based analyses of HRI in the tele-ICU workspaces.

The key challenge for the Extensive Simulation is to ensure both the simulation fidelity (Liu, Macchiarella, and Vincenzi 2008) (i.e., perceived and functional aspects of HRI in the simulation will closely replicate the real-world tele-ICU workspaces) and the reliability (i.e., HRI captured in the simulation is repeatable, reproducible, and the number of HRI instances is large enough to permit statistical inference). To address this challenge, digital twin (DT) (Grieves and Vickers 2017) and immersive simulation, two different simulation concepts developed under different contexts, are integrated under the ES simulation framework. The sections are organized as follows: Section 2 to characterize HRI in tele-ICU workspace and review the current role of simulation, Section 3 to propose the ES framework with concept of operations, Section 4 to elaborate the system architecture for the ES, followed by a proof-of-concept design, and Section 5 for discussions and conclusion.

## 2 HRI FOR CRITICAL CARE

### 2.1 Distributed Tele-ICU System and Telemedicine Use Cases

A review of 103 tele-ICU practices identified two distinct care models (Ramnath et al. 2014). One is the hub-and-spoke model performed by a central "hub" station that mediates between remote physicians and local "spoke" ICUs for centralized and continuous monitoring. To the contrary, the Virtual Consultant model (VCM) leverages distributed network of communication and telepresence technologies (e.g., telepresence robot, cart-based videoconferencing hardware, audio and video connections, and other sensors) to facilitate sporadic interactions between a patient and multiple care providers, some are onsite, and others are remotely connected. This article focuses on the VCM for its potential to scale up tele-ICU systems with the advancement of smart robots and distributed network technologies, although the hub-and-spoke model is currently the predominant implementation setup (Guinemer et al. 2021).

Under the distributed architecture, a tele-ICU system (Avilés et al. 2021) generally consists of the physical telepresence robot, robot operator, communication interfaces that link the robot and the operator, operational environment, and more broadly, the users who interact with the robot (including care providers, patients, families, and other people who randomly encounter the robot in ICU). Representative tele-ICU use cases for the VCM (Guinemer et al. 2021) include remote care delivery for community and rural areas in contexts where onsite care capacity is limited; tertiary care where continuous monitoring and scheduled rounds are warranted to improve compliance; and patient transfer between units/ hospitals in which monitoring and support is needed at the junction of care transition. This article will elaborate on these use cases for the simulation development.

### 2.2 HRI in Distributed Tele-ICU

In light of HRI (Chandrasekaran and Conrad 2015), distributed tele-ICU use cases can be classified as "contactless collaboration" (Hentout et al. 2019), in that clinical interventions are coordinated through information exchanges between a remote care provider and the onsite telepresence robot. In addition, an operation of telepresence robot involves *cooperation* between onsite care providers and the robot (e.g., during bedside monitoring), where humans and robots serve the same purpose. At the same time, human-robot coexistence, the simplest form of HRI, is also observed, where humans and robots merely share a workspace without common tasks (e.g., a random encounter of people and the robot during its navigation in a hallway). It requires the HRI design to prevent physical collision or in-hospital infection for safety.

### 2.3 Challenges to Distributed Tele-ICU in Care Practice

#### 2.3.1 Unknowns throughout the Life Cycle of Tele-ICU System

About a half of healthcare institutions reported being stuck in the early stage of contemplating, piloting, and implementing telemedicine (Lokken et al. 2020). Telepresence robots were not incorporated into routine critical care practice because of lingering concerns about infrastructure issues such as limitation of network stability, inability to open doors or travel up and down stairs, and difficulties with navigation and docking (Broadbent 2017); managerial issues with potential breaches of privacy, trust, or codes of ethics

(Lin, Abney, and Bekey 2011); and user perception of technological familiarity and acceptance (Ayatollahi, Sarabi, and Langarizadeh 2015). Behind the above issues are unknowns that might arise during tele-ICU design, deployment, operation, and maintenance (Becevic et al. 2015); for example, the knowledge of how the robot will interfere with existing clinical workflows; concerns with productivity in unusual circumstances such as high patient volumes or technical failures; and pressures to ensure patient satisfaction and safety at all times while patient and/or guardians interact with robots. This lack of operational knowledge is key motivation for the proposed high-fidelity simulation and simulation-based analyses of tele-ICU work systems.

#### 2.3.2 Emerging Opportunities in the Post COVID-19 Critical Care Delivery

Since the COVID-19 outbreak began, the combination of regulatory shifts and hospital workflow redesign has led to a huge increase in telemedicine visits (Contreras et al. 2020). In response to that emerging situation, the robotics industry has launched a new set of technological solutions for healthcare delivery. Among 395 healthcare robotic technologies recently launched to help fight the COVID-19 pandemic, the top five solutions are all associated with implementing, augmenting, or extending telemedicine (StartUs 2020). Telepresence robots have the potential to augment telemedicine by facilitating contactless monitoring and communication with patients and/or their families; recently developed telepresence robots such as Akibot (Carranza et al. 2018) combine the ability to move in a remote location with an attached high-resolution camera to support remote patient consultation, assistance, and social communication in primary, inpatient, and residential care settings.

### 2.4 Simulation for Productivity and Safety of Tele-ICU

Evidence to date reports positive effects of tele-ICU on productivity; for example, significant reduction in length of stay (LOS) and hospital mortality, possibly due to enhanced monitoring via tele-ICU to adhere to best practices and guidelines; and enhanced coverage of critical care delivery in community and rural areas (Guinemer et al. 2021). However, the effects of various tele-ICU attributes on cost effectiveness remain inconclusive (Subramanian et al. 2020). As an analytic solution, simulation can help identify factors that positively or negatively affect productivity, because it allows to predict overall productivity of tele-ICU system while quantifying the effects of specific HRI attributes (Hentout et al. 2019). In addition, simulation can be useful to improve safety and security; for example, safety simulation for HRI (Bobka et al. 2016). In the post COVID-19 era, a simulation-based prediction for the risk of airborne transmission will be a topic of interest. However, existing simulation-based analytics are limited in their abilities to fundamentally improve productivity and safety of tele-ICU. First, simulations are engineered by assuming that a certain set of system parameters and workspace conditions is given. Changes in HRI modality that go beyond this initial assumption could invalidate the simulation outcomes. Second, simulations are often designed to reproduce initial stages of a system to support design and procurement decision, rather than long-term operation and maintenance in the later stage of life cycle. And modification of the simulation to reflect the later stages can be costly and time consuming. Finally, the simulations are created and configured by engineers who are not actual users of tele-ICU. No formal method is established for the design of simulations to reflect the knowledge, experiences, and opinions of care providers and patients.

## 3 EXTENSIVE SIMULATION FRAMEWORK FOR TELE-ICU

### 3.1 Conceptualizing Extensive Simulation

This section proposes a new concept of Extensive Simulation (ES) that can potentially enhance design, productivity, and safety of tele-ICU systems by supplying realistic attributes of the constituent ICU workspace and HRI for the simulation. This concept is distinguished for its emphasis on the fidelity of system constituents. The rationale is that simulating a highly complicated and dynamically-changing system might deviate from reality, if the system’s key elements are not sufficiently realistic. Or, the fidelity of the whole system is only as high as that of its parts having the lowest fidelity (Fernández-Godino et al. 2016). DT and immersive simulation, two different simulation concepts developed under different contexts, may shed distinct lights on the method of ensuring the fidelity of parts.

In its original concept, DT refers to a broad set of "virtual information constructs that fully describes a physical manufactured product" in the context of product life-cycle management, so that any information that could be obtained from inspecting the physical product can be equally obtained from its digital replica (Grieves 2014). The following literature on DT continues to concentrate on product life-cycle management (Khan et al. 2018), in which the goal was to create and maintain a highly accurate representation of the physical twin (PT) through "bidirectional" connection to the physical manufacturing system. Compared with physical products in manufacturing setting, the status of human systems such as cognition is far more difficult to simulate with high precision due to the inherent complexity, and it remains a grand challenge for DT in healthcare.

Alternatively, immersive simulation provides a collection of techniques to elicit diverse human responses at neuropathological, affective, cognitive, or behavioral levels in a virtual environment designed to emulate realistic visual cues, interactive functions, and scenarios. The concept of immersion broadly refers to an "objective description of reality delivered by technology" that appeals to the sense of human with an "inclusive, extensive, surrounding, and vivid illusion" (Slater 2009). Healthcare domain has long adopted immersive simulation, predominantly for the training and evaluation of clinical skills, problem solving, and judgment (Rosen 2008). In this regard, the challenge of immersive simulation in healthcare workspaces is to create an inclusive, extensive, and vivid illusion of healthcare setting, so that realistic human behaviors can be observed.

## 3.2 Concept of Operations

### 3.2.1 The Scope of Tele-ICU Workspace

A general description of tele-ICU workspace (Figure 1) consists of different user groups (Table 1), basic technologies (telepresence robot and network infrastructure), and value-added components for the future extension (healthcare database, smart sensors, ICU equipment, and ICU personnel training), which will be beyond the scope of the current article. Tele-ICU system at its core is a kind of Cyber-Physical-Human system that consists of physical telepresence robot, robot operator, HRI control logic, and communication network and network interfaces that are managed by administrator. The tele-ICU system is designed to provide critical care services represented by the three use cases defined in Table 2. Tele-ICU workspace is larger in scope, including clinical task and task protocols, ICU environment, and organizational characteristics. The two user groups, patient and care provider, are classified as primary because they are essential constituents of tele-ICU service process.

Table 1. User group definition

| No | Group label | Priority in tele-ICU service | Instances |
|---|---|---|---|
| 1 | Patient | Primary | Inpatient, patient in admission, patient at discharge |
| 2 | Care provider | Primary | Intensivist, physician consultant, surgeon, nurse |
| 3 | Care coordinator | Secondary | Scheduler, care planner, receptionist |
| 4 | Technician | Secondary | Robotic operator, network administrator |

Table 2. Use case defined for tele-ICU workspace

| Use case | Description |
|---|---|
| Tele-consulting | Remote care delivery for patients in community and rural areas in contexts where onsite care capacity is limited |

| | |
|---|---|
| Bedside rounding | When continuous monitoring and scheduled rounds are warranted to improve compliance and safety in tertiary care |
| Patient transfer | Monitoring at the junction of care transition and patient transfer between units/ hospitals |

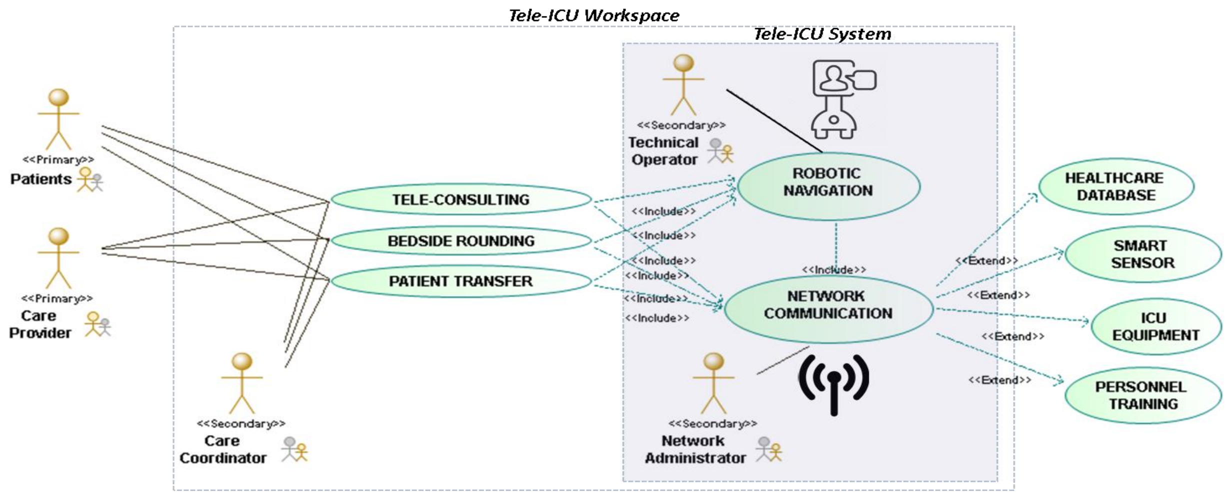


Figure 1. Defining the scope of tele-ICU system and workspace.

### 3.2.2 Goal and Objectives of ES

The proposed ES generally aims at high-precision analysis of a complex cyber-physical-human system to resolve unknowns in the design and operation of the system. For distributed tele-ICU system in particular, its high-precision analysis will be achieved by ensuring the fidelity of HRI in tele-ICU workspace. Methodologically, the ES integrates DT and immersive simulation to achieve the following objectives.

- To obtain a reliable estimation of HRI workspace: The information of HRI workspace on the hospital floor occupied by human(s) and robot during use case performance is critical for the design of layout and robotic control. For example, in routine beside rounding, the information of spatial trajectories occupied by robot and nurses is useful for the design of efficient robotic lane on the hospital floor. The spatial occupancy information is also useful to analyze spatial coverage.

- To obtain a reliable estimation of HRI worktime: The temporal information of HRI (when a robot navigation/human trip begins and ends) is useful for the design of task planning and allocation. Again in bedside rounding, this information is essential for the planning of optimized staffing and robot navigation speed to cover a given ICU area.

- To analyze contact risks: The spatiotemporal information taken together from the above objectives permits contact or proximity analysis. It helps quantify the risk of hospital-acquired infection (HAI), in which disease is transmitted by air, or by direct/ indirect contact, or a combination of both routes (Eames et al. 2009). HAI risks have been the subject of very high attention from public and government, and even higher during and after the COVID-19 pandemic (Morawska and Milton 2020). The contact analysis also helps quantify the risk of collision under heavy traffic in ICU environment such as during morning rounds or emergency situations.

### 3.2.3 ES Components

The ES combines DT and immersive simulation in sequence. Inspired by DT concept, it will first establish a bidirectional connection between a physical telepresence robot in the tele-ICU system and its digital replica that will be constructed and operated within a virtual ICU environment. The digital-twin system will "online" capture all components of ICU workspace while use cases are being executed, except the behaviors of primary user groups (i.e., patients and care providers; see Table 1). The resultant virtual tele-ICU workspace is expected to mimic the physical environment (e.g., hospital floor layout and patient bed locations), as well as the dynamic behaviors of tele-ICU system, based on real-time data from the LiDAR sensor and the system log (e.g., the robot's navigation trajectories). Once the online DT simulation is completed, it will then be used as an "offline" immersive simulation (in a sense that it is not synchronized with actual use cases being performed in ICU) as an experimental tool to collect a set of realistic human activities under the "situated" virtual tele-ICU workspace. A single or multiple users who qualify for the user group of interest will participate this offline simulation with a virtual-reality (VR) headset on and perform their simulated tasks in that experimental workspace. This simulation component is valuable for the repeatability and reproducibility of simulation outcomes under realistic human variability, a basis of statistical reliability.

This proposed integration of DT with immersive simulation will potentially overcome the fundamental limitation of current DTs in configuring human-robot collaboration (Kousi et al. 2021), which was to disproportionately concentrate on robot configuration only and neglect human's adaptability (Miller et al. 2005), possibly due to the lack of statistically-reliable knowledge about humans at work. Immersive simulation can facilitate knowledge discovery of emergent human behaviors by placing the user(s) in a highly contextualized situation. It also helps collect a large set of activity instances on a given virtual ICU environment and use cases to generalize on human actions and derive statistically-valid human models.

## 4 ES SYSTEM CONSTRUCTION

This section describes the ES system architecture, implementation, and initial design features developed for proof-of-concept. This simulation platform and simulation-based analysis methods will continue to evolve with a diverse set of use case scenarios, technological extension enabled by healthcare databases and smart sensors, and a larger population of user base including patients and care providers.

### 4.1 System Architecture for ES

The two defining characteristics of the ES are, first, bidirectional communication between PTs and DTs for optimal HRI design and configuration, and second, use of immersive simulation to actively elicit context-rich human responses while interacting with a virtual robot within a virtual environment. Figure 2 depicts the system architecture that illustrates how the ES integrates digital-twin simulation (colored in red) and immersive simulation (colored in blue) concepts.

Overall, the ES system interacts in real time with physical ICU workspace enabled by network infrastructure. Note that the User Group is now a part of the workspace rather than an external factor as defined in Figure 1, thanks to the immersive simulation process. It receives input (in a form of interactive responses) from the User Group stimulated by the Virtual Reality (VR) headset. Depending on the network capacity, it may also support multiple threads of VR steams to simulate multiple-user mode.

The digital-twin workspace constructed for immersive simulation should incorporate digital-twin robot (a real-time representation of telepresence robot, including its appearance and navigation), user group interactions (collected through VR headset and wearable sensors), and VR environment (provided by VR designers to represent an actual care environment). Once a digital-twin workspace is complete with the aid of digital-twin and immersive simulation process, it will be validated based on the two criteria of simulation fidelity and reliability. Finally, the simulation will be analyzed to provide quantified, generalize-able information on different aspects of HRI, including workspace and time, and contact analyses.

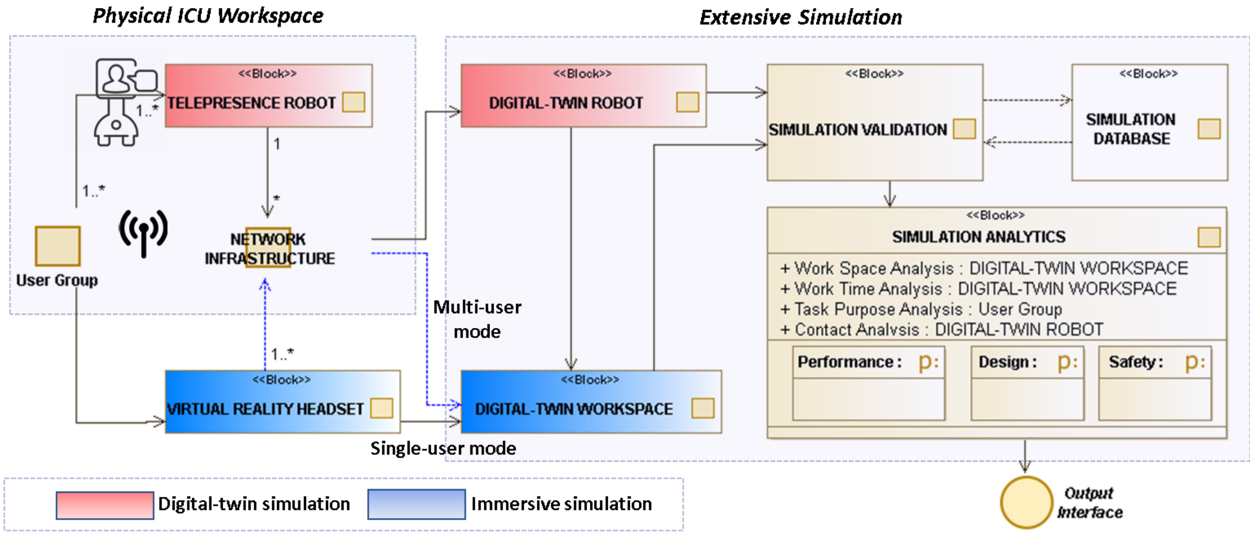


Figure 2. The ES system architecture.

## 4.2 Simulation-Based Analysis Methodology

The purpose of simulation-based analysis for the ES is to produce a reliable, generalize-able, and quantitative summary of HRI. Not all components of digital-twin workspace are used for analysis. Depending on the analytic purpose, different simulation components can be queried and visualized for more intuitive understanding of the HRI pattern. Figure 3 illustrates information flows between the PT and DT, and a module for simulation analytics.

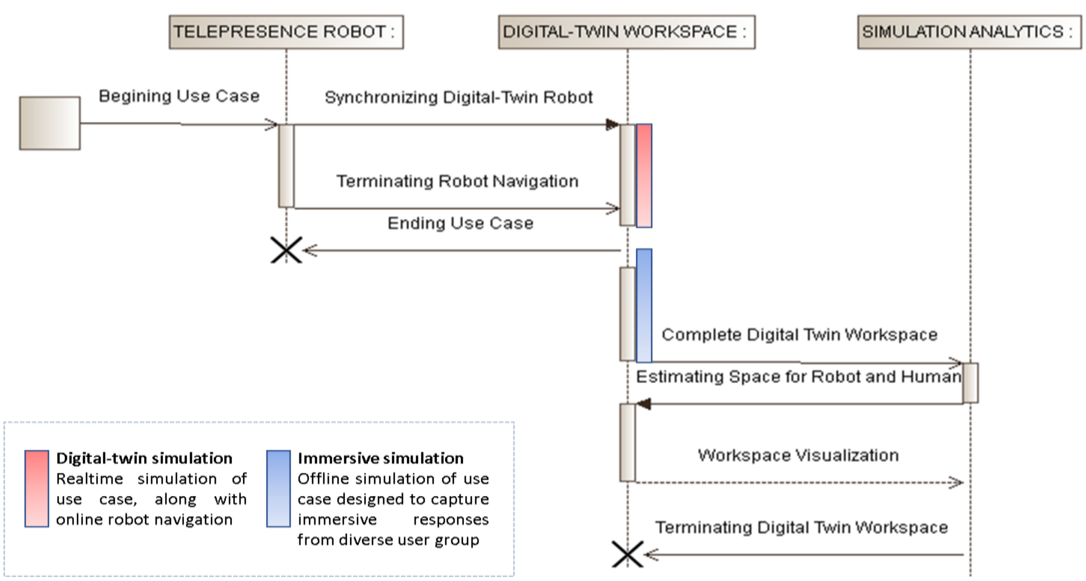


Figure 3. An illustration of simulation analytics.

## 4.3 Implementation

The technological implementation of the ES system can be characterized by three main components: the Ohmni® telepresence robot, the Robot Operating System (ROS) node network, and the Unity3D game engine. The OhmniLabs, Inc., San Jose, produced the telepresence robot which was used in this proof of concept. The company showcases additive manufacturing and modular design techniques for high customizability and extendibility. The modular and extensible software and hardware as provided the needed features for the proof of concept implementation and provides the base for future work.

The ROS serves as middleware between the high level robot applications and helps to abstract the low level components such as firmware and drivers along with providing developer tools and plug and play algorithms. The open source nature, mature developer community, and wide adoption all helped to streamline the implementation. With its vast feature set, the ROS will also help realize more complex aspects of implementing the ES.

Finally, the Unity3D game engine provided the main platform for developing the digital environment. Similar to the telepresence robot and the ROS, the Unity3D platform allows for high customizability and a robust feature set for real-time rendering and VR development. Additionally, the integration with the ROS through the TCP Connector and Endpoint packages provided a key component to the implementation of the DT. Particularly, the ROS integration allowed for the bidirectional connection for data flow and commands. These three core components were leveraged to implement the ES. Figure 4 depicts the technical architecture of the implementation.

For the Physical ICU workspace, the Jump Simulation Center located at the University of Illinois Urbana-Champaign campus was used. It is a high fidelity simulation facility designed to take advantage of VR, medical mannikins, and task trainers for immersive, experiential medical education. The simulation center contains several spaces and suites which provides an innovative hands-on instructional environment through immersive simulation for students, physicians, nurses and researchers for the University of Illinois and community partners. Being able to utilize the ICU and patient rooms for this project allowed us to replicate the hospital setting (including ventilator, bed, patient monitor, and simulated patient) in an environment that would not jeopardize patient safety, outcomes, or infectious processes. It also allowed for serial testing without interference of bed placement or disrupt discharge or admission processes that could be timely and costly in a hospital setting. Selected components of the Simulation Center were digitally replicated to construct a digital-twin workspace within the Unity3D.

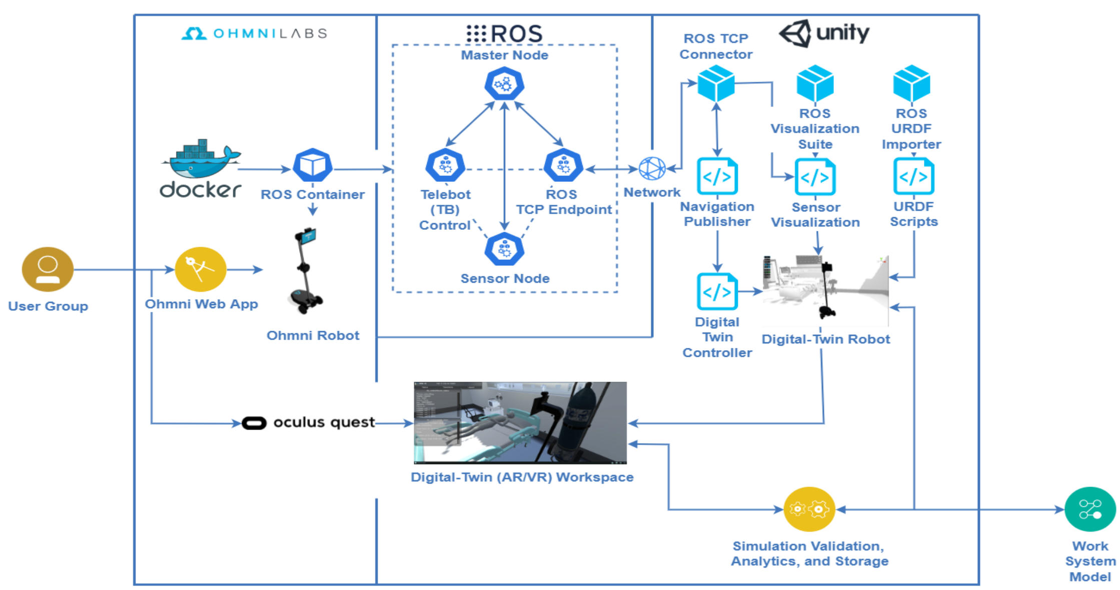


Figure 4. Technical implementation through the integration of distinct platforms.

### 4.4 Proof-of-Concept Design

The technical architecture in Figure 4 was implemented using a ROS docker image provided by the OhmniLabs Inc., to communicate with the low-level servo and motor controllers for robot navigation. This was accomplished via the OhmniLab's specialized TB Control ROS node. The Unity TCP Endpoint node provided established the bidirectional connection between the Unity environment and the TB Control node during runtime.

Figure 5. PT vs DT of the tele-ICU.

Within the Physical ICU workspace, an ICU scenario was staged using medical mannikins (SimMan3G, Laerdal, Inc.) and other medical equipment including patient bed, vital display, and mechanical ventilator. Figure 5 illustrates a snapshot of the ES featuring mirrored navigation between physical and digital environments. Realtime navigation commands were issued from the user on the digital side, while data such as wheel odometry, transform pose data, and battery voltage status on the physical side was communicated back to the Unity environment.

## 5 DISCUSSIONS AND CONCLUSION

### 5.1 Discussions

The minimal functionality of the ES platform was realized to showcase a proof of concept and to validate simple bi-directional data flow between the DT environment and the physical telepresence robot. Limitations were noted in navigation as further optimizations in of the physically-based parameters within the ES are need such as friction and mass. Nonetheless, a simple AI nurse rounding and patient scenario was implemented using Unity's AI and Navigation package. Further development will focus on increasing the fidelity of the ES within Unity along with implementing simulation analytics.

In future studies, the human behavior captured by users interacting with the online and offline simulation will be studied. From these findings, tasks along either contexts will be identified and then categorized as being owned by either the robot, the human operator, or the care provider. Issues regarding priority and ownership hierarchy of both tasks and control will be examined. In future iterations of the ES, technology failures will also be simulated to account for events including network outages, battery power constraints, ICU power outages, and sensor failures. Finally, user acceptance and satisfaction will be evaluated from both the VR user and in-person perspectives.

Other interdisciplinary topics of future research include the cost analysis of implementation with respect to equitable and secure access especially within understaffed, underfunded, and underserved healthcare regions. Additionally, longitudinal studies would be beneficial to study the impact of medical telepresence robotics on patient safety and healthcare work systems.

The ES platform provides the toolset to develop, test, and iterate on various HRI scenarios and designs within the medical domain before implementation on-site. However, the ES platform also provides the necessary flexibility and extendibility for robotic control, analytics, and system feedback after implementation.

### 5.2 Conclusion

This article proposed an immersive digital-twin simulation framework, dubbed Extensive Simulation (ES), aimed at high-precision analysis of human-robot interaction (HRI) for tele-ICU. This article defined the scope of HRI in the context of tele-ICU workspace, conceptualized the ES, and elaborated its concept of operation and system architecture, followed by system implementation with a proof of concept. For implementing the PT, Ohmni® telepresence robot was remotely operated by a group of physician, nursing staff, technician, and coordinator, in the Jump Simulation Center located on the university campus. For the DT, the Unity3D platform integrated the Robot Operating System node network to establish bidirectional communication with the PT. The ES framework advances the DT concept by including humans into the loop via immersive simulation, which will help to reliably capture diverse human behaviors and construct human model for tele-ICU work system.

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